Original Article

Super-elasticity in vitro assessment of CuNiTi wires according to their Austenite finish temperature and the imposed displacement

Noémie Copelovici[a]; Maï-Linh Tran[b]; François Lefebvre[c]; Pascal Laheurte[d]; Delphine Wagner[e]

ABSTRACT

Objectives: To assess the super-elasticity of CuNiTi wires (Ormco, Glendora, Calif) according to their Austenite finish temperature (Af) and to the imposed displacement. The secondary objective was to compare the wire dimensions with the stated measurements and to study interbatch variability.

Materials and Methods: 10 types of CuNiTi wires (Ormco, Glendora, Calif) ($n = 350$) were investigated at $36 \pm 1°C$, with conventional brackets (Victory Series, 3M Unitek, Monrovia, Calif). Tensile test with coronoapical displacement ranging from 1 to 5 mm of the canine bracket was imposed. The wire dimensions were initially measured from two batches ($n = 10$).

Results: Dimensional heterogeneity varied by $\pm$ 2.00% compared to the manufacturer's data, and even up to 5.54% for 0.014-inch CuNiTi ($P = .00069$). However, all unloading forces were reproducible. In decreasing order, the forces delivered by a CuNiTi 27 were greater than those with CuNiTi 35 and 40. The super-elasticity was expressed only for displacements of 1 to 2 mm, at best up to 3 mm for 0.014-inch CuNiTi 27.

Conclusions: The value of Af as well as the amount of imposed displacement seem to influence the expression of the super-elasticity of CuNiTi wires and the amount of corrected malocclusion. Among the tested wires, under these experimental conditions, 0.014-inch wire could be suitable as a first archwire. CuNiTi 35, therefore, seems to offer the best compromise among the force level, the expression of super-elasticity and the amount of malocclusion correction. (*Angle Orthod.* 2022;92:388–395.)

KEY WORDS: Orthodontics; Malocclusion; Orthodontic wires; Shape memory alloys; Mechanical tests

INTRODUCTION

To conduct orthodontic treatment without tooth extraction, practitioners generally follow an archwire sequence consisting of three to four wires.[1] Shape memory alloys (SMAs) are widely used during the first phase due to their properties, especially super-elasticity (SE).[1–3] In 1994, three categories of CuNiTi (Ormco, Glendora, Calif) were marketed, each named according to its Austenite finish temperature (Af).[4] The addition of copper was effective at stabilizing the super-elasticity characteristics.[5]

Material tests are carried out according to the corresponding ISO (International Organization for Standardization) standards. Governed by assumptions from the materials resistance laws, these define material behavior. Thus, SE was defined as the ability of a specimen to return to its initial shape when the deformation stopped, without plastic deformation, under certain temperature conditions (T > Af), reflected on a load/deflection graph by a "plateau" upon

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Accepted: November 2021. Submitted: July 2021.
Published Online: January 31, 2022

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 DOI: 10.2319/027121-575.1

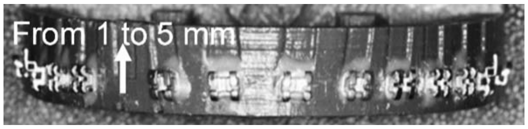


Figure 1. Experimental setup simulating a high ectopic right maxillary canine displaced from 1 to 5 mm.

unloading.[6] Above Af, the instability of stress-induced martensite leads to a reversible transformation into austenite. The homogeneity of the experimental protocols allows comparisons between studies.[7,8] Their limitation is that they do not represent clinical conditions accurately. Mulling et al. expressed reservations about the presence of a super-elastic plateau during bending tests when interbracket distances and clinical deformities were applied.[9] Ren et al. also questioned the expression of SE at intraoral temperature due to the values of phase transformation temperatures of some of the studied alloys.[10] Thus, some authors have proposed adding brackets in the design of the setups.[3,11–16] The tests would then be structural tests.

Mechanical properties depend on the wire dimensions, their composition, and the manufacturing process. Lombardo et al. found some dimensional variability of square and rectangular wires.[17] When the focus was on Af, Pompei-Reynolds and Kanavakis also reported some heterogeneity.[18] These results may suggest that there is a certain heterogeneity between wires, potentially influencing the recorded measures.

No previous study of the behavior of CuNiTi tested the entire range of Af for the different dimensions that may be part of an archwire sequence and for displacements ranging from 1 to 5 mm, under conditions approaching those of the intraoral cavity. The purpose of this study was to evaluate: (1) the expression of the SE of CuNiTi wires according to their respective Af and the amount of imposed displacement, and (2) the amount of correction of the malocclusion for different wire / brackets combinations. The objective was to determine if these two parameters could be used as a key element in the clinical choice of archwires. The secondary objective was to quantify the interbatch dimensional variability.

MATERIALS AND METHODS

Materials

The 0.018-inch conventional brackets (Victory, 3M Unitek, Monrovia, Calif) were placed on a maxillary artificial arch (Figure 1) simulating a high ectopic right maxillary canine, according to a previous published methodology.[19] Table 1 summarizes the 350 samples of CuNiTi 27, 35, and 40 wires (Ormco, Glendora, Calif) tested and their respective dimensions.

Methods

Measurements of the archwire dimensions. One operator measured the dimensions of five successive wires extracted from two different batches using a digital caliper (Holex digital caliper 150 mm, Holex, Hoffman GmbH, Achim, Germany; 0.01-mm accuracy). A total of 50 as-received wires were tested (Table 1). For rectangular wires, the short side, called height, was analyzed separately from the long side, called width. Mean dimensions were compared with each other as well as with the values claimed by the manufacturer. Mean dimensions from two different batches were also compared. A one-way *t*-test was used to determine the significance of any differences. The null hypothesis was that all samples and batches would have the same mean dimensions and correspond to the value declared by the manufacturer. H_0 was rejected if $P < .05$.

Measurements of the mechanical tests and CuNiTi behavior assessment. Tensile tests were performed by the same operator on a universal testing machine (Zwick/Roell Z020, Zwick GmbH, Ulm, Germany). The crosshead speed was set at 1 mm/minutes. Artificial saliva[20] was used and the temperature was controlled at 36 ± 1°C (ISO 15,841). A delay of 3 minutes was observed before proceeding with a test.[21] The loading

Table 1. Characteristics and Number of Samples Used per Test[a]

	CuNiTi 27				CuNiTi 35				CuNiTi 40	
	0.014-inch	0.016-inch	0.018-inch	0.016 × 0.022-inch	0.016-inch	0.018-inch	0.016 × 0.022-inch	0.017 × 0.025-inch	0.016 × 0.022-inch	0.017 × 0.025-inch
Interwire and interbatch variability (n)	5	5	5	5	5	5	5	5	5	5
Tests to record the mechanical efforts (n)	30	30	30	30	30	30	30	30	30	30
Total (n)	35	35	35	35	35	35	35	35	35	35

[a] 0.014-inch = 0.356 mm; 0.016-inch = 0.406 mm; 0.018-inch = 0.457 mm; 0.016 × 0.022-inch = 0.406 × 0.559 mm^2; 0.017 × 0.025-inch = 0.432 × 0.635 mm^2.

and unloading forces (N) were registered at the center of the right maxillary canine bracket by the load cell. The displacements ranged from 1 to 5 mm. For each category of wires, six measurements were carried out per displacement (Table 1). New wire and ligatures, placed with a Straight Shooter ligature gun (TP Orthodontics, LaPorte, Ind), were systematically positioned.[22]

The curves, representing the force (N) as a function of displacement (mm), were analyzed. On the loading curves, two points were studied: the super-elasticity threshold determined by the tangent method, and the maximum displacement. Upon unloading, when super-elasticity was present, the start and end values of the plateau were noted. They were also obtained by the tangent method.

To determine the factors involved in the mechanical tests recorded, statistical analysis was conducted using intraclass correlation coefficients (ICC).

Amount of malocclusion correction (MC). The MC was calculated using the methodology proposed by Montasser et al. (equation 1)[21]:

$$\mathrm{MC} = \textit{mean obtained displacement}\,(\textit{mm}) / \text{initial imposed displacement}\,(\text{mm}) \times 100 \quad (1)$$

A one-way *t*-test was used to determine the significance of any differences. The null hypothesis was that the amount of malocclusion correction obtained for one archwire dimension tested would be identical for the three types of CuNiTi tested. H_o was rejected if $P < .05$.

RESULTS

Archwire Dimensions (Figure 2)

Measured dimensions were heterogeneous, varying on average $\pm$ 2.00% from the standard. The 0.014-inch CuNiTi 27 was an exception, with statistical dimensional differences up to 5.54% ($P = .00069$).

The dimensions were either undersized or, more rarely, oversized. The rectangular wires widths are all undersized, with statistical significance for the 0.017 $\times$ 0.025-inch CuNiTi 35 and 40.

CuNiTi 27 wires showed the most statistically significant interbatch differences. Conversely, CuNiTi 40 had the greatest interbatch homogeneity.

Mechanical Testing and CuNiTi Behavior Assessment (Figure 3)

CuNiTi 27 wires exhibited the greatest measurement dispersion, followed by the CuNiTi 35 and CuNiTi 40 wires. A trend similar to that observed in dimensional variability was found, in which CuNiTi 27 showed the greatest dimensional dispersion. This was attributed to the variability among the wires and not to the methodology applied (ICC $=$ 0.71). Loading curves were more dispersed than unloading curves, and the dispersion increased with displacement.

Under loading conditions, the super-elastic threshold was observed for a displacement ranging from 0.5 to 1 mm, whatever the value of Af of the tested CuNiTi. The values of the threshold were more correlated with the dimension of the archwire than with the value of Af (ICC $=$ 0.1). Beyond this threshold, super-elasticity was observed. On unloading curves, when a plateau was observed, the forces acquired were systematically higher with CuNiTi 27 than with CuNiTi 35 and with CuNiTi 40. Exerted forces were well grouped, despite a certain heterogeneity of the archwire dimensions. On average, the plateau represented 71.29% of the imposed displacement for the CuNiTi 27, 73.5% for CuNiTi 35, and 55% for CuNiTi 40 (Table 2). On the other hand, the super-elasticity could not be described for displacements of more than 1 mm and 2 mm, respectively, for CuNiTi 40 and 35. Only 0.014-inch CuNiTi 27 allowed an expression of super-elasticity up to 3 mm.

Amount of Malocclusion Correction (Figure 4)

Only malocclusions of 1 to 2 mm were more than 50% corrected, except with CuNiTi 40. 0.014-inch CuNiTi 27 was the only wire to allow almost complete corrections of malocclusions up to 3 mm. For displacements of 4 and 5 mm, the average amount of malocclusion correction was 21.75% and 20.33%, respectively.

DISCUSSION

Interwire Variability

The results obtained were in agreement with those presented in the literature, with archwire cross-sections larger or smaller than those claimed by the manufacturers.[23–26] Lefebvre et al. also observed an increase of wire-slot play due to oversizing of the slots and the divergence of the slot walls.[27] These features, however, have the advantage of reducing the friction during sliding techniques.

Interwire variability had also been the subject of published studies. Hemingway et al. reported that two of the 10 tested wires from the same batch delivered greater force than the others.[28] Conversely, during the unloading phase, the force differences recorded between the wires were minor. Pompei-Reynolds and Kanavakis also demonstrated interbatch variations between CuNiTi 27, 35, and 40 from the same manufacturer.[18] In addition, variable values of Af have also been reported in the literature.[16]

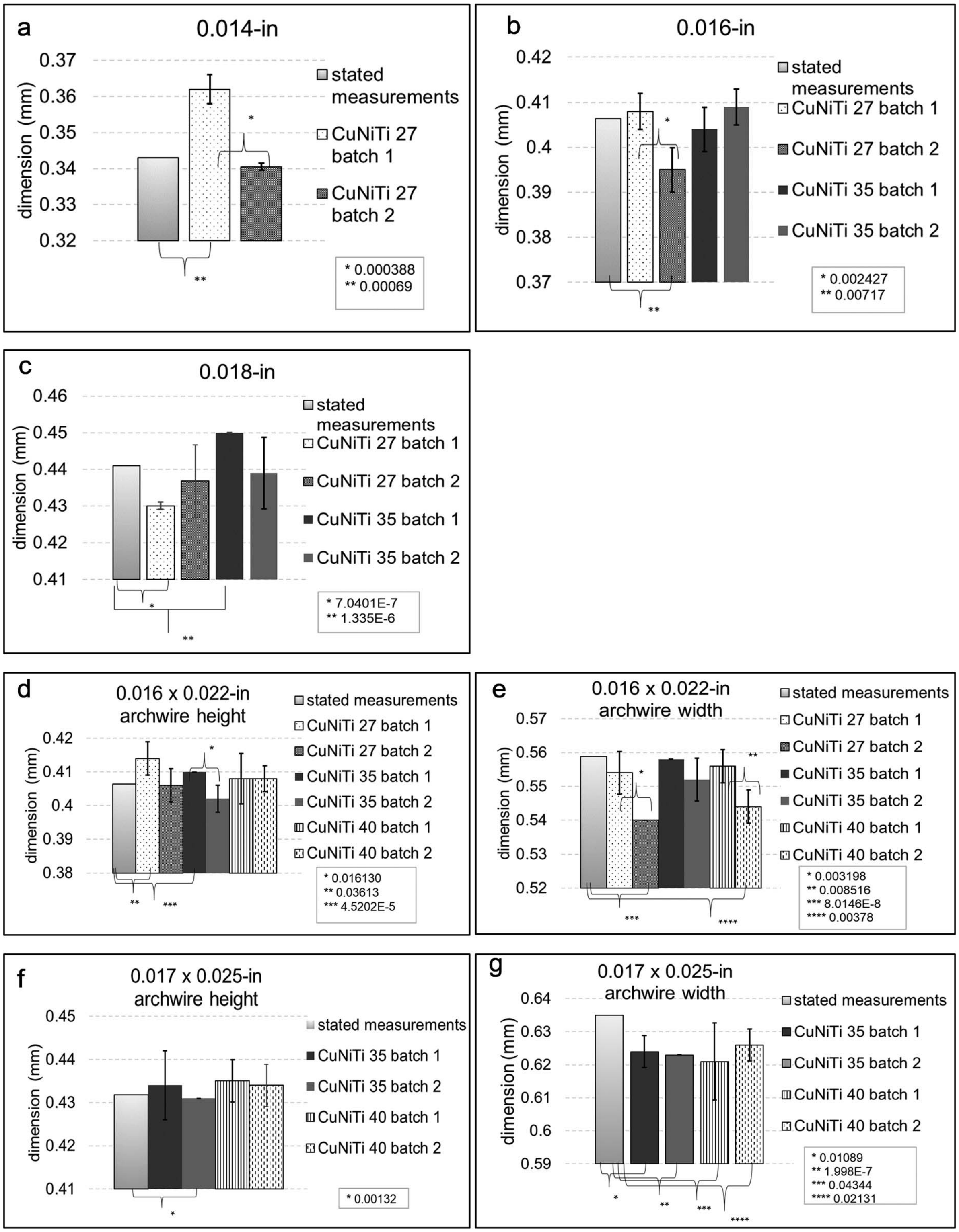


Figure 2. (a to g): Comparison of the average dimensions of the CuNiTi 27, 35, and 40 wires to the stated ones claimed by the manufacturer and assessment of interbatch variability.

Dimensional heterogeneity as well as metallurgical characteristics could explain the dispersion of measurements that was sometimes observed. Indeed, these characteristics will condition the first appearance of martensite under stress and then of a plastic phase inside the material during loading. These phenomena may not be identical depending on the wires tested. Clinically, even for archwires chosen from the same

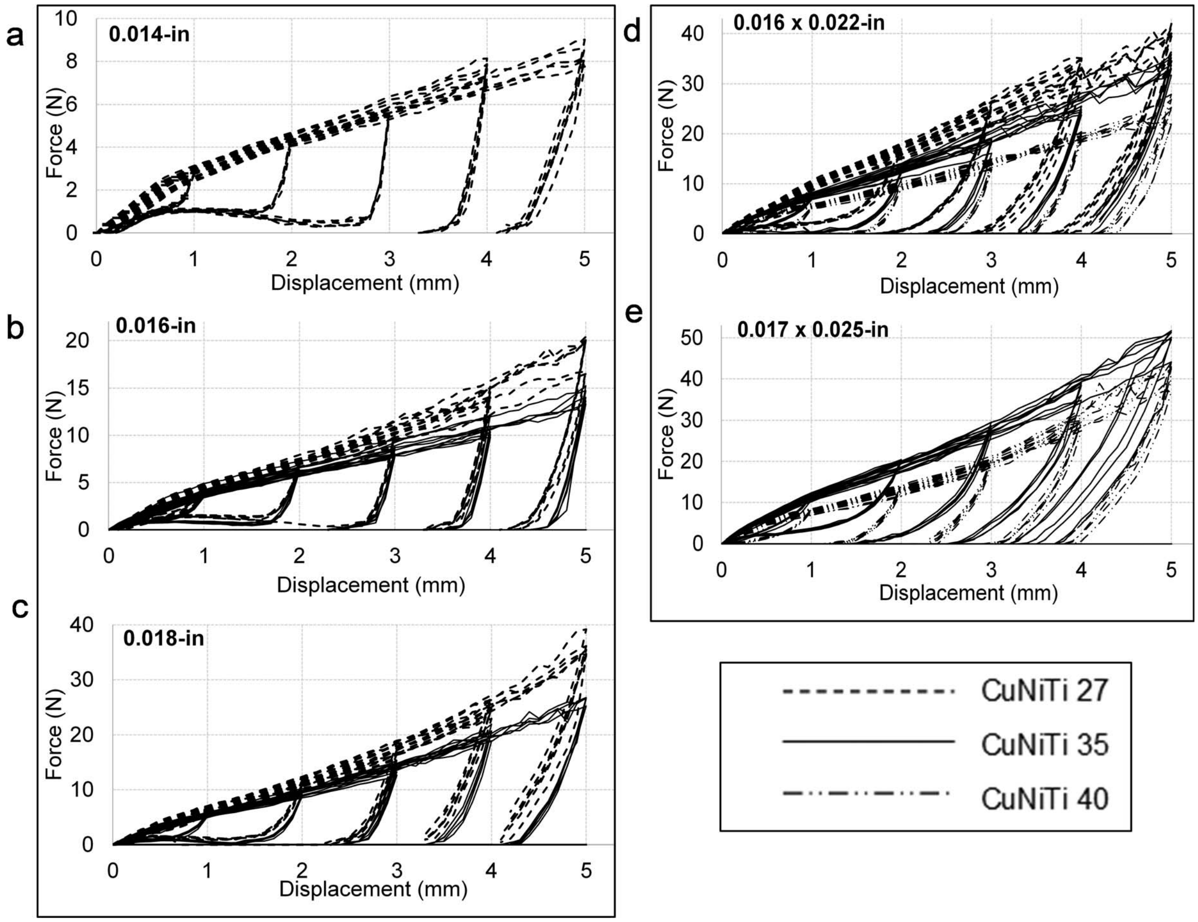


Figure 3. (a to e): The loading/unloading graphs represent the displacement (mm) as a function of the force applied (N).

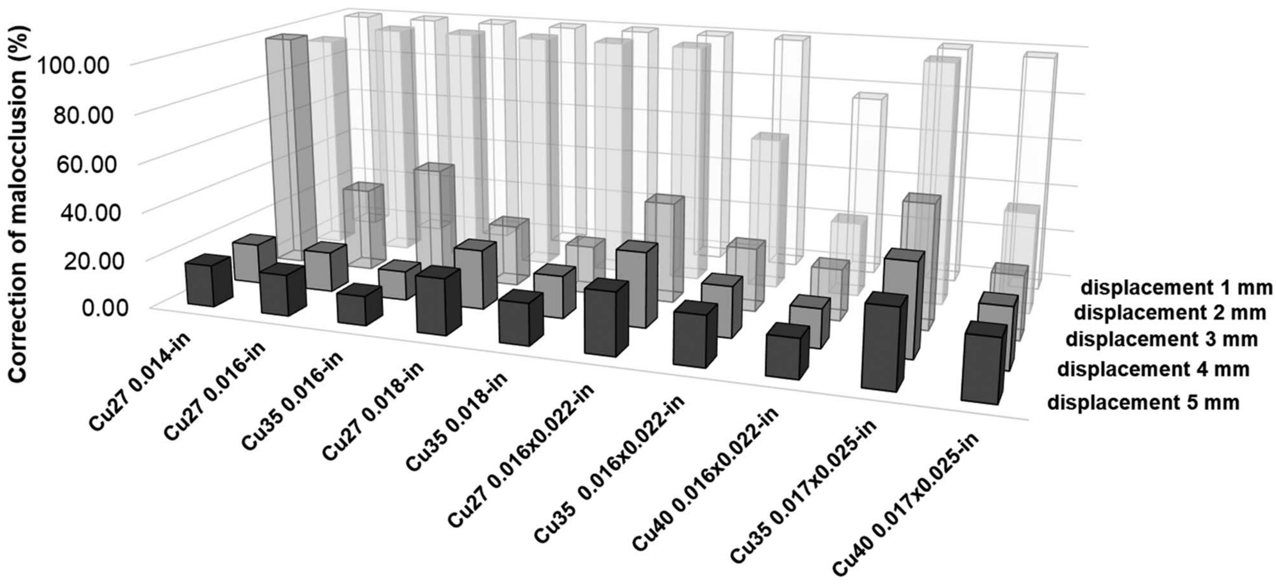
manufacturer, with the same characteristics (size, composition, and Af), it should be expected that the mechanical properties and the forces recorded would not be strictly similar.

Phase Transformation Temperatures

The mechanical forces applied depend on the crystallographic structure of the alloy and its state at the test (or intraoral) temperature. Austenite is more rigid than martensite. Thus, since CuNiTi 27 was the only wire to be perfectly austenitic at 36°C, its crystallographic state may explain the greater forces recorded. CuNiTi 40 is not fully austenitic at 36°C and stress-induced martensite is formed during the displacement. These two elements may explain that this alloy delivered the lowest forces but, at the same time, expressed the least super-elasticity. A second phase transformation temperature, Austenite start temperature As, and the temperature transition range (TTR) have been reported in the literature to influence the variation of force delivered.[16,29]

Table 2. Forces Recorded at Extent of the Displacement Within the Super-Elastic Plateau

	CuNiti 27				CuNiti 35				CuNiti 40	
	0.014-inch	0.016-inch	0.018-inch	0.016 × 0.022-inch	0.016-inch	0.018-inch	0.016 × 0.022-inch	0.017 × 0.025-inch	0.016 × 0.022-inch	0.017 × 0.025-inch
Length of the plateau (% of mean-imposed displacement)	71.17	66.5	75	72.5	73.9	75	72.5	72.5	50	60
Force (N) [min; max]	[0.67; 1.38]	[0.77; 2.25]	[0.53; 3.58]	[0.55; 5.61]	[0.46; 1.24]	[0.41; 1.92]	[0.53; 3.04]	[0.63; 7.18]	[0.11; 1.75]	[0.10; 2.72]



	Cu27 0.014-in	Cu27 0.016-in	Cu35 0.016-in	Cu27 0.018-in	Cu35 0.018-in	Cu27 0.016x0.022-in	Cu35 0.016x0.022-in	Cu40 0.016x0.022-in	Cu35 0.017x0.025-in	Cu40 0.017x0.025-in
displacement 5 mm	17.33	17.00	12.00	23.00	17.00	25.33	20.33	15.67	31.33	24.33
displacement 4 mm	16.67	16.67	12.08	24.58	17.50	30.83	20.83	15.83	37.92	24.58
displacement 3 mm	99.44	35.00	46.67	25.56	20.00	41.67	26.11	21.11	51.11	26.11
displacement 2 mm	93.33	100.00	100.00	100.00	100.00	100.00	63.33	30.83	100.00	41.67
displacement 1 mm	100.00	100.00	100.00	100.00	100.00	100.00	100.00	76.67	100.00	98.33

P = 0.9 P = 0.07 P = 0.13 P = 0.11 P = 0.11

*P = 0.008

Figure 4. Amount of malocclusion correction for the CuNiTi wires associated with conventional brackets. (* indicates statistically significant difference.)

Amount of Imposed Displacement

The literature generally reported mechanical forces applied for 2 or even 3 mm of deflection.[25,30] SMAs, however, admittedly allow large amplitude displacements with relatively constant forces during unloading, which is particularly suitable for solving moderate to severe malocclusions. According to the results of the current study, the super-elasticity threshold under loading was expressed between 0.5 and 1 mm. Up to these values, the wires were still mainly in the elastic domain. A hysteresis phenomenon was observed without a real super-elastic plateau. Therefore, mechanical forces applied for larger displacements up to 5 mm were tested. Unfortunately, the expected super-elasticity was not found for such displacements.

Amount of Malocclusion Correction

According to the current results and previous publications, the first wire to favor seems to be the 0.014-inch CuNiTi 27, correcting malocclusion up to 3 mm.[30,31] Montasser et al. had previously noticed that even a 0.014-inch wire caused high forces.[21] Smaller diameters could be beneficial especially for CuNiTi 35.

Study Limitations

This work would deserve to be the subject of additional studies, with 0.022-inch conventional[32] and self-ligating brackets, and a comparison according to their material (metallic vs esthetic).

In general, the forces recorded were substantial compared to those recommended to promote tooth movement. To extrude one tooth, 38 to 40 g (ie, 0.38 to 0.4 N) would be necessary to correct a high, buccally displaced canine.[33] However, it is not recommended to retain numerical values of in vitro experiments.[13] In addition, the values obtained were the conjunction of a vertical force applied and those due to the resistance to sliding. Naziris et al. showed that the unloading forces experimentally acquired with a static model were overestimated by 56 $\pm$ 11% in the presence of elastomeric ligatures.[34] These conclusions, applied to the current work, are clinically interesting as the force values at the level of the plateau would therefore be lower and, thus, more biologically compatible.

CONCLUSIONS

- The wire dimensions were heterogeneous but are within a manufacturing tolerance of 2.00%, except for the 0.014-inch CuNiTi 27 (5.54%; $P = .00069$). The widths of the rectangular archwires were significantly undersized.
- Austenite finish temperature and the imposed displacement are two major criteria involved when the super-elasticity of CuNiTi 27, 35, and 40 wire is assessed.
- According to the experimental conditions, super-elasticity of CuNiTi 27, 35, and 40 was observed for displacements of 1 and 2 mm, and the plateau represented between 55% and 70% of the total displacement. The 0.014-inch CuNiTi 27 wire corrected the greatest amount of malocclusion, up to 3 mm.
- CuNiTi 35 offered best compromise between the level of applied force, the existence of a super-elastic property and the amount of malocclusion correction. Conversely, CuNiTi 27 appeared to exert significant high forces while CuNiTi 40 would have a limited expression of super-elasticity.

ACKNOWLEDGMENTS

We would like to thank Pr. N. Bahlouli, Dr. D. George, A. Wolf, C. Munsch and J. Aron for their contribution to this work.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This study was financially supported by the ICube laboratory, Strasbourg, through an internal call for projects, 2019.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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